Project ID: #eems033

U.S. DEPARTMENT OF ENERGY

SMARTMOBILITY

Systems and Modeling for Accelerated Research in Transportation

Truck Cooperative Adaptive Cruise Control/Platooning Testing: Measuring Energy Savings and Aerodynamic Interactions

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DOE VTO Annual Merit Review
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ENERGY EFFICIENT MOBILITY SYSTEMS PROGRAM INVESTIGATES

MOBILITY ENERGY PRODUCTIVITY

THROUGH FIVE EEMS ACTIVITY AREAS

Advanced R&D Projects

Living Labs

Smart Mobility Lab Consortium

Core Evaluation & Simulation Tools

HPC4Mobility & Big Transportation Data Analytics

SMART MOBILITY LAB

CONSORTIUM

7 labs, 30+ projects, 65 researchers, $34M* over 3 years.

- Advanced Fueling Infrastructure
- Urban Science
- Multi-Modal Transport
- Mobility Decision Science
- Connected & Automated Vehicles

*Based on anticipated funding

OVERVIEW

- **Timeline**
  - **Project start date: Jan 1 2017**
  - **Project end date: Jun 30 2019**
  - **Percent complete: 50%**
- **Budget**
  - **Total project funding: $848K**
    - **100% DOE/VTO**
  - **Funding for FY 2017: $493K**
    - **LBL: $407K**
    - **NREL: $86K**
  - **Funding for FY 2018: $355K**
    - **LBL: $269K**
    - **NREL: 86K**
- **Barriers**
  - **It is necessary to quantify fuel saving benefit for CACC truck operation at high speed for different scenarios**
- **Partners**
  - **Berkeley Lab (project lead)**
  - **Transport Canada**
  - **National Research Council (NRC) of Canada**
  - **National Renewable Energy Laboratory (NREL)**
  - **UC Berkeley**

RELEVANCE AND OBJECTIVES

- **Challenges**
  - **The energy impact of truck CACC and Platooning can be more accurately determined through physical experiments and should be quantified to highlight two key effects: changes due to aerodynamic drag and vehicle speed variations; it is also critical to perform physical experiments to validate modeling results**
  - **Objectives for FY 17**
    - **Investigate truck CACC/Platooning impact on energy use at high speed due to aerodynamic drag reduction and speed changes for fundamental maneuvers**
  - **Objectives for FY 18**
    - **Investigate truck CACC/Platooning impact on energy use at a signalized intersection with Active Traffic Signal Control (ATSC)**
  - **Objectives for FY 19 (go/no-go)**
    - **Demonstrate energy savings of a 3-Truck CACC/Platoon when driving along a freeway corridor with real-world traffic**

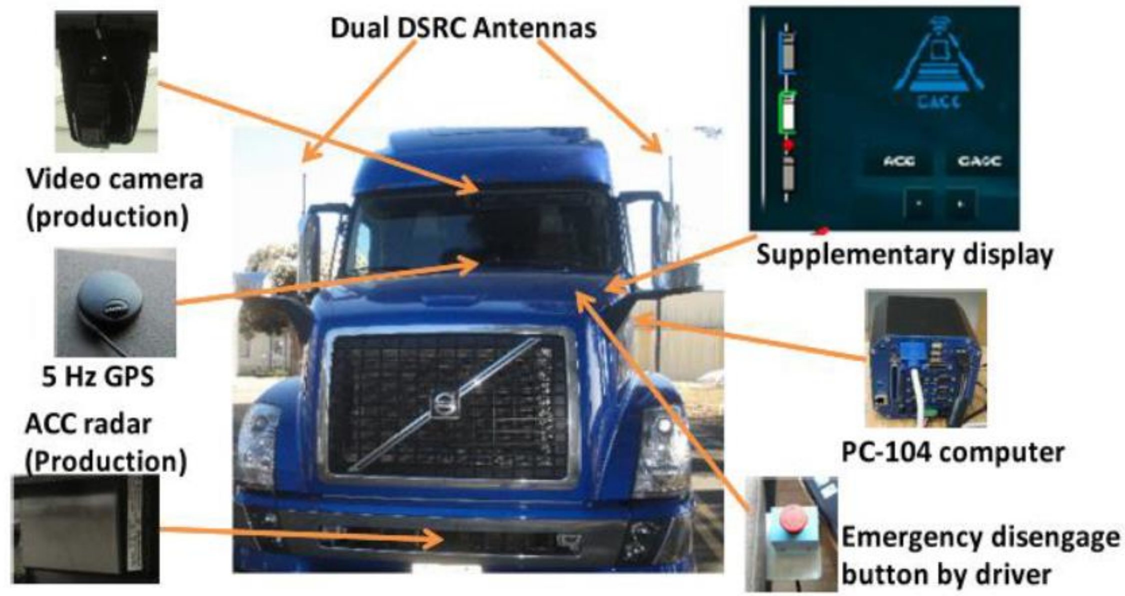
APPROACH AND MILESTONES – FY17

- **Relevance:** **moving people and goods more efficiently with reduced energy consumption for sustainable mobility in transportation with CAV technologies**

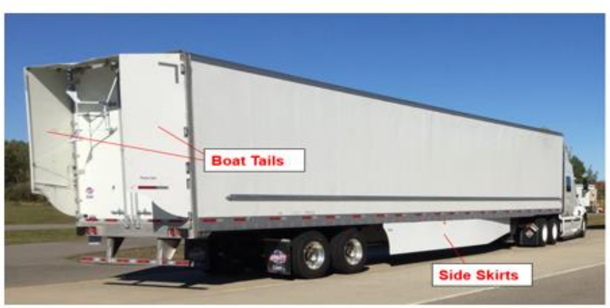
Fuel Consumption Evaluation for Truck CACC Operation at Freeway Speed - FY 17														
SAMRT Mobility CAVs Pillar														
Approaches / Months	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1.Determine test plan including scenarios and schedules														
2. Prepare control code for all test scenarios for efficient tests														
3. Refine CACC control for performance improvement														
4. Move 3 Volvo trucks with CACC to Transport Canada Test Site														
5. Modify tractors with extra sensors (NRC Canada), boat tail etc.														
6. Conduct the test strictly following SAE J1321 test procedures														
7. Conduct test data analysis and writing papers														

TECHNICAL ACCOMPLISHMENTS – FY17

- **System preparations**



Fuel tank mounting/removal & weighing



Trailer modifications

Air speed & pressure sensors

TECHNICAL ACCOMPLISHMENTS – FY17

- **Testing truck CACC fuel consumption impact**
  - **Vehicle mass: *29,500kg* or *65,000lb***
  - **Following at different constant speeds (*50 mph* and *65 mph*)**
  - **Following at different Time-Gap (or D-Gap: *4 m – 87 m*)**
  - **2-truck CACC and 3-truck CACC**
  - **For variety of maneuvers:**
    - **Single truck ACC**
    - **cut-in between truck 1 & 2, and truck 2 & 3**
    - **Speed variation between 55mph ~ 65mph**
    - **Midsize SUV leading 2-truck & 3-truck CACC strings following**
    - **LCV: Single tractor with two fully loaded trailers**

TECHNICAL ACCOMPLISHMENTS – FY17

- **Test Track & Scenarios:**


4m CACC following

Transport Canada's Motor Vehicle Test Centre, Blainville, Québec


Speed variation with 18m D-Gap


Long combination vehicle testing


Cut-in CACC string with 35m D-Gap

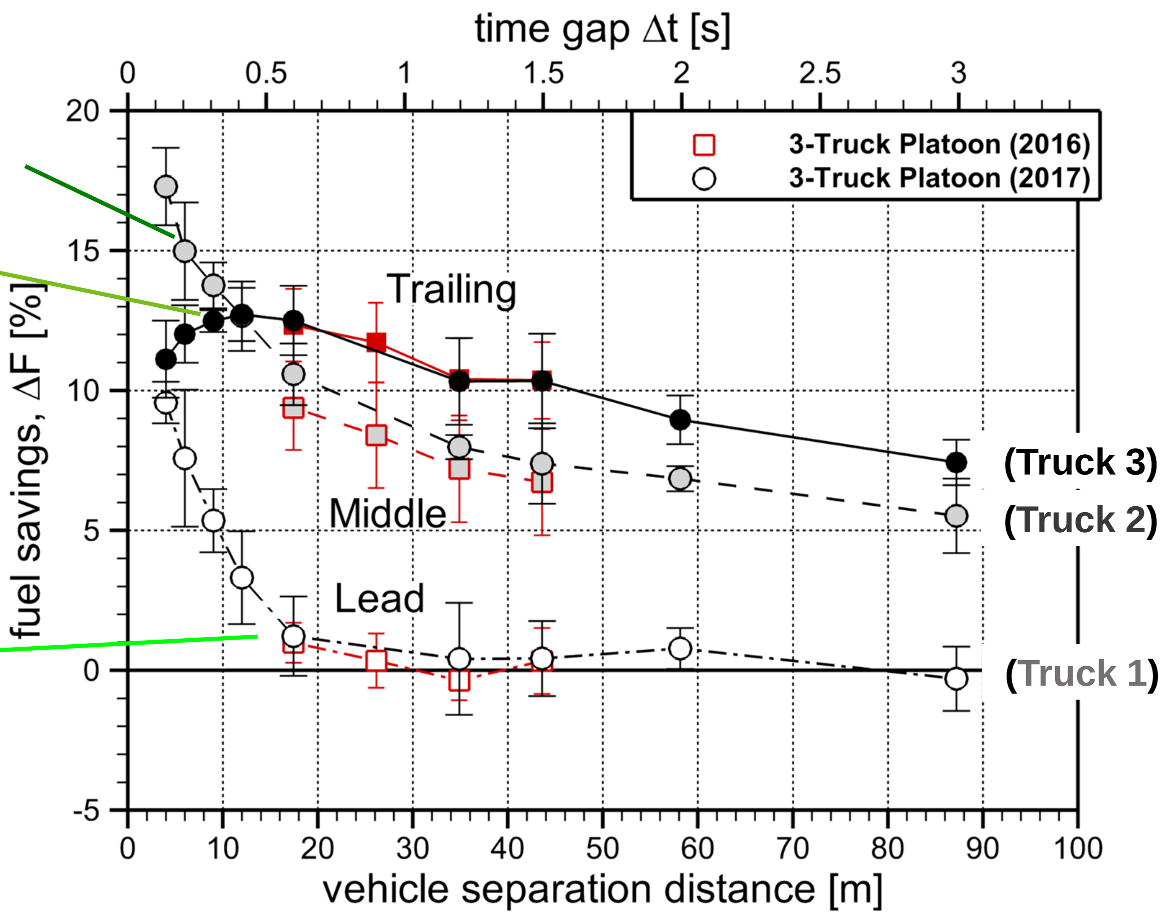

Manually driven SUV leading 3-truck CACC with 56m separation & 12m between trucks

TECHNICAL ACCOMPLISHMENTS: Test Results – FY17

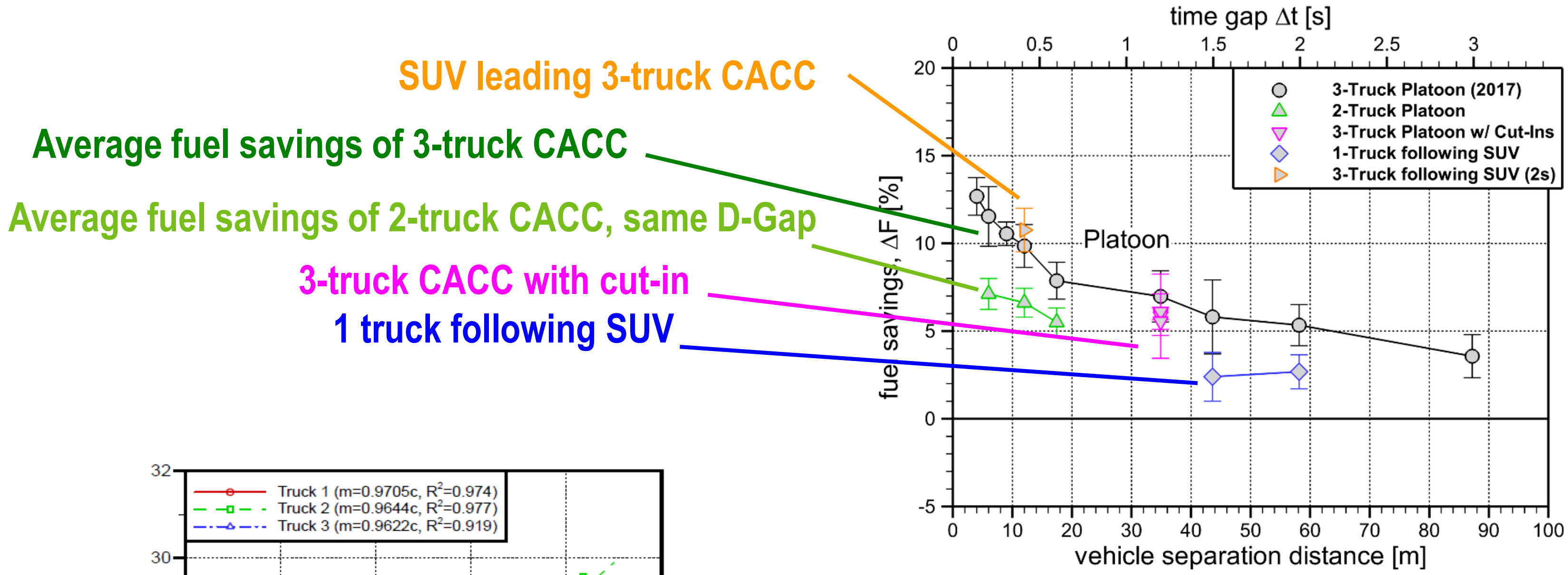
Truck 2 has highest savings at short D-Gap

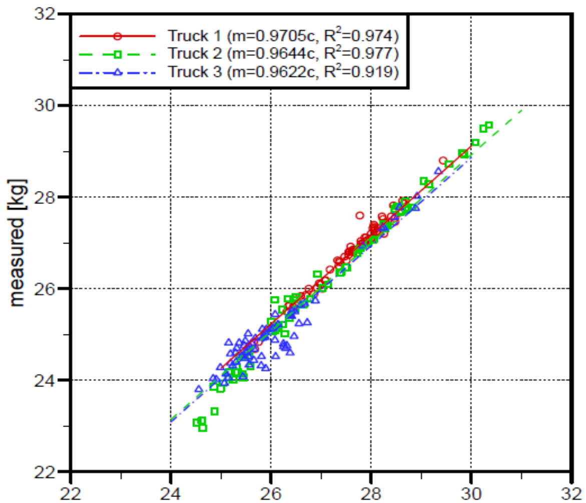
Truck 3 savings decrease at short D-Gap

Truck 1 has savings at short D-Gap



TECHNICAL ACCOMPLISHMENTS: Test Results – FY17





Fuel consumption [kg] estimated from CAN Bus fuel rate data

Fuel consumption: measured vs. estimated from CAN-Bus fuel rate

COLLABORATION WITH OTHER INSTITUTIONS – FY17

- **Transport Canada provided about $1M supporting the tests**
- **National Research Council of Canada (NRC – Brian McAuliffe) managed the tests and conducted data collection and partial data analysis for fuel savings**
- **NREL (Michael Lammert) partially conducted data analysis for fuel savings**
- **LBNL team conducted CAN-Bus fuel rate data analysis**
- **LBNL team provided truck CACC test (CAN-Bus) data and some modeling parameters to ANL for Autonomie model calibration**

REMAINING CHALLENGES AND BARRIERS

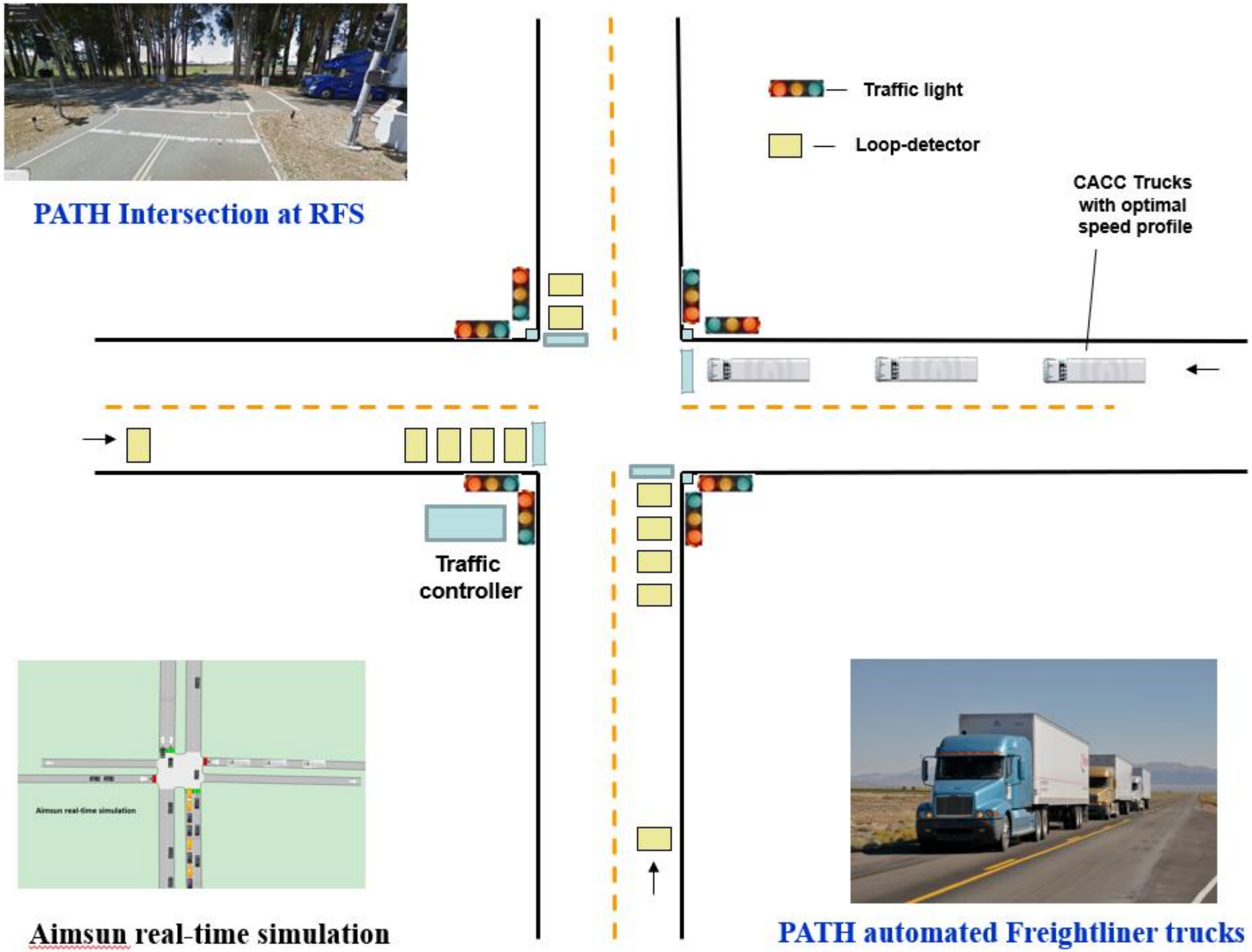
- **To quantify fuel saving benefit for CACC truck operation at a signalized intersection through experiments**

- **To quantify fuel saving benefit for CACC truck operation along a freeway corridor with real-world traffic through experiments**

APPROACH – FY18

- **Concept of Operation: Simulation and hardware in-the-loop CACC truck operation at signalized intersection with integrated ATSC**
  - **Real-time (RT) simulation of a typical intersection traffic with ATSC for optimal green distribution according to traffic demands of all movements with CACC trucks embedded in simulation**
  - **Developing wireless communication (V2I & V2V) for system integration**
  - **CACC trucks driving with automatic longitudinal control**
  - **The optimal reference speed trajectory (to minimize total delays and fuel consumption) will be used by the lead truck for control**
  - **Able to repeat the tests for many times with similar traffic pattern**

APPROACH: Concept of Operation – FY18



PATH Intersection at RFS

Aimsun real-time simulation

PATH automated Freightliner trucks

APPROACH – FY18

1. **Update 3 Freightliner trucks for full speed range CACC**
2. **Model intersection traffic with typical field demands in Aimsun**
3. **Develop ATSC for flexible green times according to simulated traffic**
4. **Generate optimal reference speed profile for CACC trucks to:**
   - **reduce speed variations (including *Stop&Go*)**
   - **improve traffic throughput and reduce total delay of all movements**
   - **consider some drivetrain characteristics**
5. **Implement wireless communication among central control computer, Aimsun real-time simulation, traffic controller, and CACC trucks**
6. **Integrate the system**
7. **Evaluate of CACC truck fuel consumption using CAN-Bus fuel rate after multiple tests with similar traffic pattern**

N.B. Any proposed future work is subject to change based on funding levels

MILESTONES – FY18

Fuel Consumption Evaluation for Optimal Truck CACC Operation at Signalized Intersection - Schedule																
SAMRT Mobility CAVs Pillar																
Subtasks / Months	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1. Update 3 Freightliner trucks for full speed range CACC																
2. Model PATH intersection traffic with typical field demand data in Aimsun																
3. Develop traffic signal control (ATSC) for flexible green distribution																
4. Develop optimal reference speed profile for CACC trucks																
5. Develop V2V & V2I between CACC trucks, traffic signal control, Real-timre Aimsun simulation																
6. Integrate the overall system																
7. Systematically evaluate of CACC truck fuel consumption using CAN-Bus fuel rate after multiple tests																

PROGRESSES – FY18

1. **Partially updated one Freightliner truck**
2. **Started working on the computer systems**
3. **Developed a draft project plan and the Concept of Operation**
4. **Started modeling the intersection**

APPROACH – FY19

1) Fix the automatic service brake control problem on 3 Volvo CACC trucks
2) Refine CACC control for performance improvement on graded road
3) Refine CACC control for performance with 3 different load levels: empty trailer, half loaded and fully loaded
4) Modify rental trailers with boat tails and side skirts
5) Select a freeway corridor with medium to high traffic and road grade
6) Hire and train professional truck drivers or incorporate with a freight movement truck company
7) Iteratively improve the system if necessary with driver feedback
8) Extensive test/operate with three CACC trucks and collect test data
9) Analyze CACC truck fuel consumption using CAN-Bus fuel rate data

N.B. Any proposed future work is subject to change based on funding levels

SUMMARY

- CACC/Platoon fuel saving observed for wide range of Distances (D-Gaps)
- Other maneuvers' effects on fuel consumption are not significant
- Truck CACC showed significant energy savings for followers
- Leader also got fuel savings if D-Gap < 9~10 m
- Crossing point around 12m for truck 2 and truck 3:
  - D-Gap shorter than 12m truck 2 saves more
  - D-Gap longer than 12m truck 3 saves more
- Consistent with the results evaluated with CAN-Bus data
- Results applicable to alternative powertrain vehicles
- Data used for simulation and fuel consumption models for truck CACC
- Fuel consumption test for 3-truck CACC operation at a signalized intersection with real-time simulation in the loop (FY18)
- Fuel consumption test for 3-truck CACC operation along a freeway corridor with real-world traffic (FY19, go/no-go)

RESPONSES TO PREVIOUS YEAR REVIEWERS' COMMENTS

This project was not reviewed last year.

QUESTIONS?

BACKUP: ROAD CURVATURE AFFECT – FY17

- Road curvature effect on Average Fuel Savings vs. single truck run across all test scenarios for three trucks

	No yaw rate limit	Yaw rate < 0.573 [deg/s]	Yaw rate < 0.286 [deg/s]
Truck 1	5.0%	5.2%	5.1%
Truck 2	11.5%	11.9%	12.0%
Truck 3	11.0%	12.0%	12.1%

Micro-Simulation of Truck Platooning with Cooperative Adaptive Cruise Control: Model Development and a Case Study

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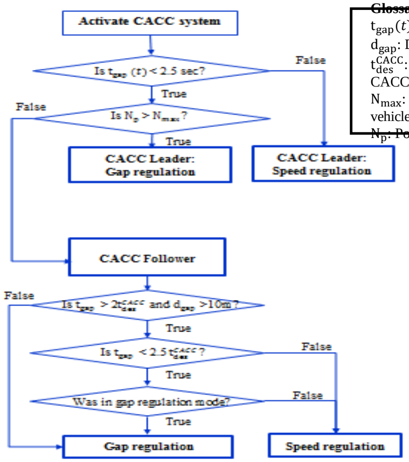
O. D. Altan, Federal Highway Administration

ABSTRACT

- Objective: Developed a micro-simulation model of heavy truck CACC when trucks share a freeway with manually driven passenger cars.
- Car following models: Developed for CACC, ACC, and CC
- Other behavioral models: Implemented lane changing, lane change cooperation, lane use restrictions, and switch from automated mode to manual mode
- Case study: Calibrated Aimsun model for a 15-mile corridor Studied effect of penetration rate on speed and VMT

MECHANISM OF AUTOMATIC VEHICLE FOLLOWING



Glossary:
$t_{gap}(t)$: Time gap at time t
d_{gap}: Distance gap
t_{des}^{CACC}: Desired time gap in CACC
N_{max}: Maximum number of vehicle in a platoon
N_p: Position in platoon

CAR FOLLOWING MODEL

$$a_{target}(t) = Max\big(b_f, Min(a_F(t), a_m(t), a_G(t))\big)$$

b_f: Max braking rate
$a_F(t)$: Acc. rate to reach free flow speed
$a_G(t)$: Gipps deceleration component
$a_m(t)$: Acc. rate for a given driving mode. For manual mode, the Newell model is used. For automated modes the following models are used.

Car Following Model (Cont.)

For Cruise Control (CC) mode:

$$a_m(t+1) = 0.3907(v_{ref}(t) - v(t))$$

$v_{ref}(t)$: Reference speed
$v(t)$: Speed of the subject vehicle

For Adaptive CC (ACC) mode:

$$a_m(t+1) = 0.0561\big[d(t) - t_{des}^{ACC} v(t)\big] + 0.3393\big[v_{prec}(t) - v(t)\big]$$

$d(t)$: Distance gap
t_{des}^{ACC}: Desired time gap, selected to be 2.2 sec
$v_{prec}(t)$: Speed of the preceding vehicle

For Cooperative ACC (CACC) mode:

$$a_m(t+1) = 0.0074\,\big[d(t) - t_{des}^{CACC} v(t)\big] + 0.0805\,\big[v_{prec}(t) - v(t) - t_{des}^{CACC} a(t)\big]$$

t_{des}^{CACC}:Desired time gap, evenly distributed between 1.2 sec and 1.5 sec

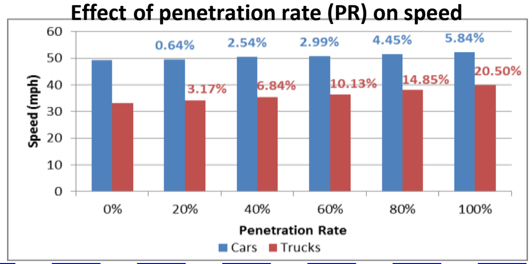
CASE STUDY: I-1710 NB

15-mile corridor with loop detector locations

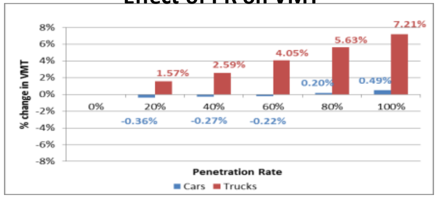
Calibrated parameters

Parameter	Calibrated value
Reaction time	1.3 sec
Gap for manual trucks	2.4 sec
Gap for manual cars	1.25 sec
Theta in Gipps model	0.2* τ_r
Max Acc. for cars	2.5 m/s^2
Max Dec. for cars	3 m/s^2
Min. speed difference to consider friction	10 m/s

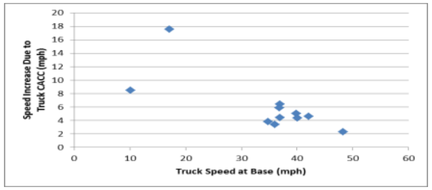
Effect of penetration rate (PR) on speed



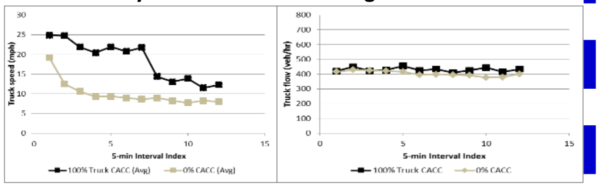
Effect of PR on VMT



Effect of 100% PR on speed at detector locations:



Traffic dynamic at the most congested detector:



CONCLUDING REMARKS

- Developed a framework to simulate automated truck platoon, manual passenger cars and manual trucks
- Comparison of 0% penetration rate vs. 100%:

For trucks: Speed and VMT increased by 20.5 % and 7.2%, respectively
For cars: Speed increased by 5.8%; marginal effect on VMT

ACKNOWLEDGMENT

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